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KEPLER OBSERVATIONS OF TRANSITING HOT COMPACT OBJECTS

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ABSTRACT

Kepler photometry has revealed two unusual transiting companions: one orbiting an early A-star and the other orbiting a late B-star. In both cases, the occultation of the companion is deeper than the transit. The occultation and transit with follow-up optical spectroscopy reveal a 9400 K early A-star, KOI-74 (KIC 6889235), with a companion in a 5.2 day orbit with a radius of 0.08 $R_\odot$ and a 10,000 K late B-star KOI-81 (KIC 8823868) that has a companion in a 24 day orbit with a radius of 0.2 $R_\odot$. We infer a temperature of 12,250 K for KOI-74b and 13,500 K for KOI-81b. We present 43 days of high duty cycle, 30 minute cadence photometry, with models demonstrating the intriguing properties of these objects, and speculate on their nature.

Key words: stars: individual (KOI-74, KIC 6889235, KOI-81, KIC 8823868)

Online-only material: color figures

1. INTRODUCTION

The *Kepler Mission* was designed to find transiting Earth-like planets in the habitable zones of other stars (Borucki et al. 2010a). To accomplish this feat, *Kepler* was launched into a heliocentric, Earth-trailing orbit allowing stars to be continuously monitored for the lifetime of the mission. A natural product of the mission is that other objects that are Earth-sized or larger that transit the host star can be detected. This includes stellar companions such as M-dwarfs and non-stellar companions such as brown dwarfs (BDs) and white dwarfs (WDs).

Observations of a stellar system with a smaller companion that orbits along our line of sight will be seen to move in front (transit) and behind (occultation) the host star. The transit light curve will have a curved "U" shape due to limb darkening of the stellar surface. The occultation will have a flat bottom and sharp egress and ingress as the flux contribution from the companion is completely obscured. From the shape of the stellar transit, the ratio of the companion and stellar radii and the scaled semimajor axis ($a/R_\star$) can be determined. The term $a/R_\star$ is related to the mean stellar density. The depth of the occultation gives the ratio of the surface brightness of the companion and stellar host integrated over the observed bandpass.

We present 43 days of high duty cycle, ultra-precise photometry of two transiting objects that have radii similar to Jupiter and effective temperatures >10,000 K. KOI-74b may have properties similar to a low-mass WD, in that it is compact and hot and its radius combined with a rough estimate of its mass is consistent with an internal structure dominated by electron degeneracy. KOI-81b has a radius consistent with either a late M-dwarf, BD, or Jupiter-sized planet, but this picture is inconsistent with its observed temperature and is also likely a WD.

2. *KEPLER* PHOTOMETRY AND TRANSIT FITS

The top panels of Figures 1 and 2 show 43 days of photometry from the *Kepler* instrument with 1σ error bars. The observations have a cadence of 30 minutes. The gap seen near HJD 2454965 is due to the transmission of data to the Earth and marks the gap between *Q0* and *Q1* observations (Koch et al. 2010a). The light curve for KOI-81 shows periodicity at 0.72 d. This signal was removed prior to the transit fits by masking off the transit and eclipsing and fitting a sinusoidal curve to the light curve.

The bottom panels of Figures 1 and 2 show the observations phased with the orbital period. The bottom curve and data are centered on the transit, whereas the upper curve and data are centered on the occultation. The points near the transit are shown with stars and pluses where the different symbols indicate odd and even transits, respectively. Measurements taken during the occultation are shown with open circles.

The data were filtered with a running median boxcar with a width of 10 days. Transit models are computed using the analytic formulas of Mandel & Agol (2002) with nonlinear limb

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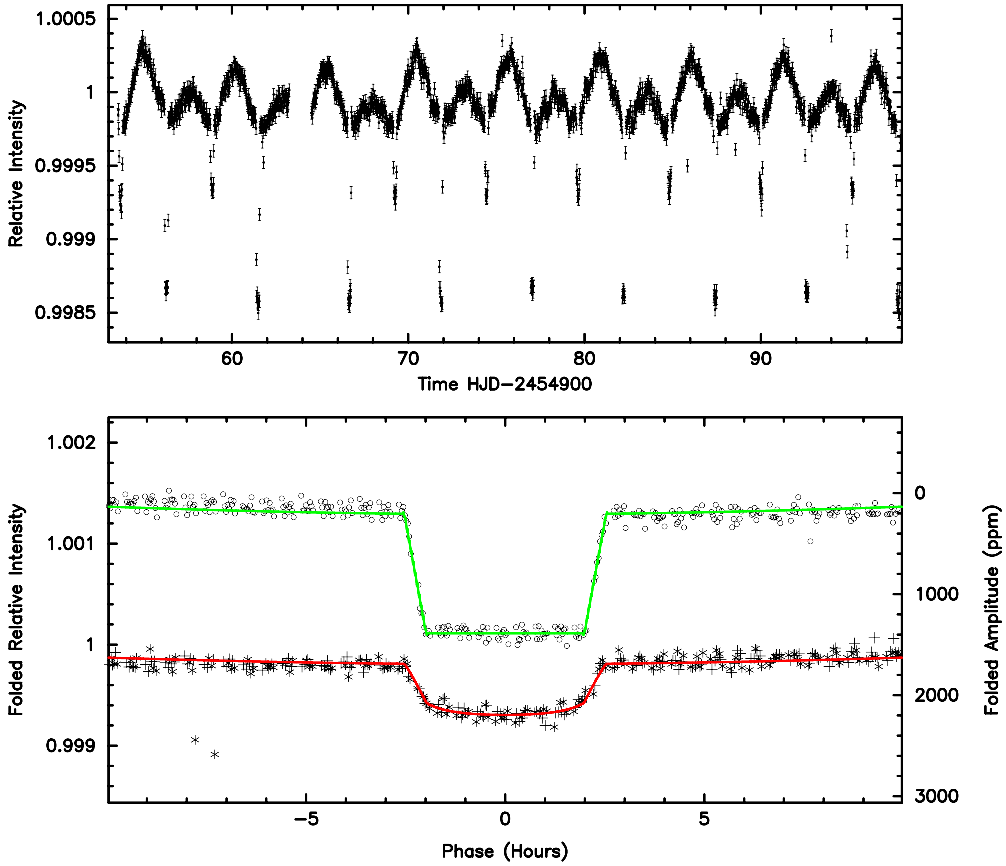

Figure 1. Phased light curve of KOI-74 containing eight transits and nine occultations observed by the *Kepler* photometry between 2009 May 2 and 2009 June 15. The upper panel shows the full 43-day time series after detrending. The bottom panel shows the light curve folded with the orbital period. The lower curve shows the occultation, with the fitted transit model overplotted in red and corresponding scale to the left. The upper curve covers the expected time of occultation, with the fitted model overplotted in green with corresponding scale found to the right. Odd and even transits are marked with stars and pluses, respectively, and measurements near the occultation are shown with circles.

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darkening. The data are fit for the center of transit time, period, impact parameter (b), the scaled planetary radius ($R/R_\star$), and $\zeta/R_\star$. The last term, $\zeta/R_\star$, is related to the transit duration ($T_d = 2(\zeta/R_\star)^{-1}$) and the mean stellar density (Pál et al. 2009). The transit models are shown in Figures 1 and 2 by the red (lower) line. The occultation is modeled by assuming no limb darkening for the occulted object and shown by the green (upper) line. The transit model assumes that the companion does not emit. While not true, this is a good approximation as the companions KOI-74b and KOI-81b are 800 and 200 times less luminous than the host stars; thus, the dilution only alters the companion radius at the 1% level. We also assumed a circular orbit in our model fits.

Optical spectroscopy obtained at the Kitt Peak 2.1 m was used to estimate KOI-74 as spectral type A1V with $T_{\rm eff} = 9400 \pm 150$ K and KOI-81 as B9-A0V with $T_{\rm eff} = 10000 \pm 150$ K. With the stellar density from the transit light curve and $T_{\rm eff}$ from spectroscopy, the stellar mass and radius were estimated using the $\rho_\star$ method as described in Borucki et al. (2010b). This allows us to model the companion radii, orbital period, inclination angle, and occultation depth, which we list in Table 1 as described in Koch et al. (2010b).

2.1. *Temperatures of the Companions*

The occultation is deeper than the transit for both KOI-74 and KOI-81, indicating the companions have a larger surface brightness as compared to the stellar host. The spectroscopically determined effective temperature and the transit-determined stellar density with the $\rho_\star$ method provide luminosity estimates of the stars. If we assume that the occultation depths are bolometric, then the depth of the occultation gives the luminosity ratio of the star and companion. The estimated luminosities of the stars and companions are listed in Table 1. Assuming the companions act as blackbodies and using the radii determined from the transit fit, we find temperatures of 12289 ± 340 K and 13430 ± 490 K for KOI-74b and KOI-81b, respectively.

2.2. *Mass Estimation*

KOI-74 and KOI-81 exhibit variations with a periodicity equal to one-half the orbital period and presenting amplitudes of ∼193 ppm and ∼50 ppm, respectively. The KOI-74 light curve also exhibits variability with an amplitude of ∼116 ppm with a period equal to the orbital period. There are various ways to interpret these variations. We could be seeing spot activity induced on the stellar surface from a magnetic interaction between the star and companion. This would be similar to activity seen in the planet hosting system HD179949 (Shkolnik et al. 2004) or τ Bootis (Walker et al. 2008). The variations could also be phase locked due to tidal distortions of the host star. In the later scenario, we can attempt to estimate the mass of the companion.

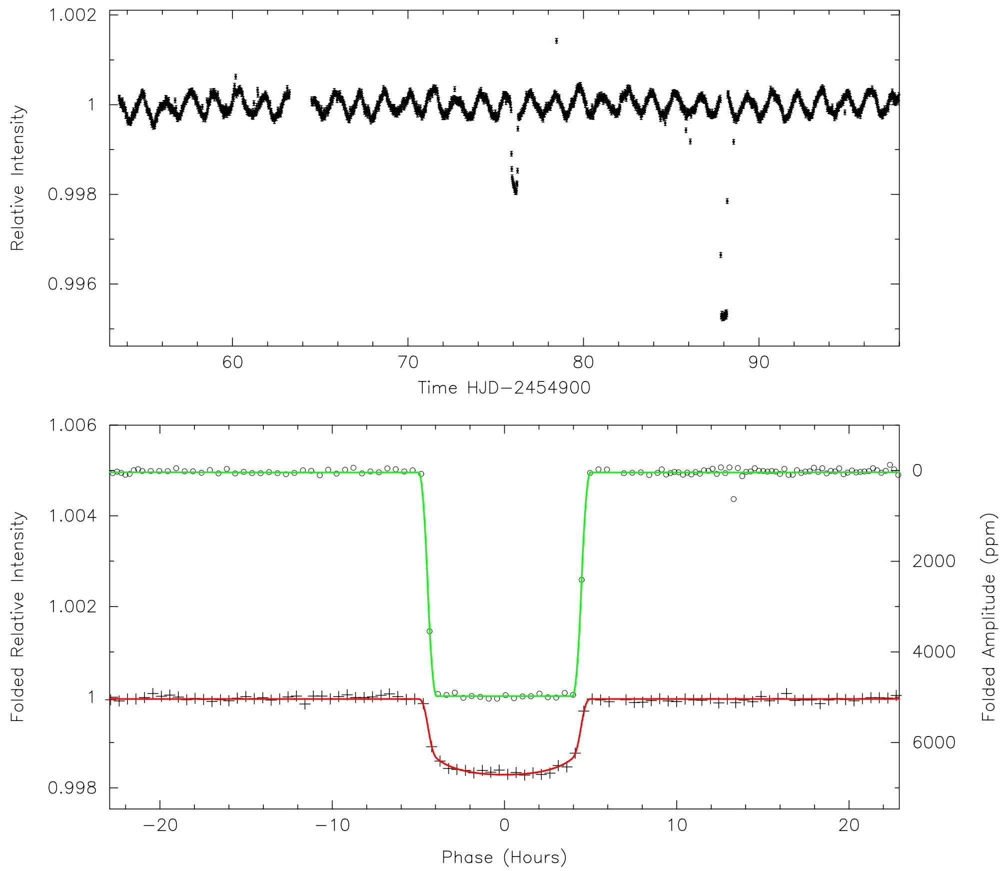

Figure 2. Phased light curve of KOI-81 containing a single transit and occultation observed by the *Kepler* photometry between 2009 May 2 and 2009 June 15. The upper panel shows the full 43 day time series after detrending. The bottom panel shows the transit and occultation after removal of periodicity seen 0.72 c day^{-1}. See Figure 1 for further details.

(A color version of this figure is available in the online journal.)

Table 1
Modeled Parameters for KOI-74 and KOI-81

KOI-74	Star	Companion
Radius	$1.899^{+0.043}_{-0.051}\ R_\odot$	$0.0393^{+0.0009}_{-0.0013}\ R_\odot$
Mass	$2.22^{+0.10}_{-0.14}\ M_\odot$	0.02–0.11 $M_\odot$
Luminosity	$25.6 \pm 2.4\ L_\odot$	$0.0317 \pm 0.0060\ L_\odot$
$T_{\rm eff}$	9400 ± 150 K	12289 ± 340 K
Epoch		$2454958.87995 \pm 0.00036$ HJD
Period		5.188754 ± 0.000083 days
i		88.8 ± 0.5 deg
Occultation depth		1238.2 ± 6.6 ppm
KOI-81	Star	Companion
Radius	$2.93 \pm 0.14\ R_\odot$	$0.115 \pm 0.006\ R_\odot$
Mass	$2.71^{+0.19}_{-0.11}\ M_\odot$	0.02–0.2 $M_\odot$
Luminosity	$77.3 \pm 9.6\ L_\odot$	$0.387 \pm 0.096\ L_\odot$
$T_{\rm eff}$	10000 ± 150 K	13430 ± 490 K
Epoch		$2454976.06981 \pm 0.00095$ HJD
Period		23.8776 ± 0.0020 days
i		88.2 ± 0.3 deg
Occultation depth		4977 ± 16 ppm

Notes. The stellar radius, mass, and luminosity are determined from the $\rho_\star$ method. The stellar temperatures are spectroscopically determined. The radius of the companion, period, i, epoch, and occultation depth are based on fits to the transit and occultation photometry. The mass of the planet is estimated from the amplitude of variations phase locked to the orbital period. The companion luminosities and temperatures are estimated assuming a bolometric occultation depth and blackbody behavior.

Ellipsoidal variations show two maxima and minima per orbital revolution. This variability is due the changing observed stellar cross section, reflection effects due to emission and absorption from each component, and gravity darkening. Morris (1985) found from a cosine expansion of the double wave characteristic of the variations that the amplitude of the light variations is given by $\Delta M = f(\tau, U_1) q R_\star^3 \sin^3(i)/a^3$, where q is the mass ratio of the companion and star, and τ and U_1 express the gravity and limb-darkening terms that describe the surface profile of the distorted star with a radius of $R_\star$ with a companion in an orbit with inclination i with a semimajor axis a. Adopting gravity and limb-darkening coefficients from Table II of Beech (1989), we estimate the mass of KOI-74b $\sim$ 0.08 $M_\odot$ and KOI-81b $\sim$ 0.19 $M_\odot$. These relations are valid when the tidally perturbed stellar surface is in hydrostatic equilibrium. An important issue is addressed below.

The ratio of the tidal acceleration to the star's surface gravity is given by

$$\epsilon \equiv \frac{M_p}{M_\star}\left(\frac{R_\star}{a}\right)^3, \quad (1)$$

where $M_\star$ and M_p are the mass of the star and companion, respectively, $R_\star$ is the stellar radius, and a is the semimajor axis. This gives a rough measure of the amplitude of the ellipsoidal variability. Assuming that the system is in tidal equilibrium, Equation (16) of Pfahl et al. (2008) can also be used to estimate the mass of the system. Adding this prescription to our transit model allows us to fit for the companion mass. We find that

KOI-74b has a mass of $\sim 0.11\,M_\odot$ and KOI-81b has a mass of $\sim 0.21\,M_\odot$.

The assumption of tidal equilibrium works well for short period binaries where both members have similar masses. Tidal dissipation circularizes the orbit and synchronizes the stellar rotation period to the orbital period. When the masses are not similar there is no reason to expect the rotation and orbital periods to synchronize, thus the assumption of tidal equilibrium may be invalid.

As shown by Pfahl et al. (2008), the tidal-equilibrium model works well for stars with deep convective atmospheres where flux perturbations arise from changes in the local effective gravity. This is not the case for stars such as KOI-74 and KOI-81 with radiative atmospheres. Tidal forcing of radiative regions could produce significant deviations from hydrostatic balance as gravity waves can penetrate the interiors. Simulations indicate that the observed oscillations can be greater than 10ϵ for stars with $M_\star > 1.4\,M_\odot$.

If the companion is the remnant of a much larger star and has experienced an episode of mass loss, then the rotational and orbital periods may have already been synchronized. In this case, the companions likely have significant mass. We plan to obtain follow-up spectroscopic observations to search for radial velocity changes. Such observations will place firm limits on the mass of the companions. Until then, we allow ϵ to be up to 10 times larger in our estimate for the masses of the companions listed in Table 1 to account for the possibility that the flux variations are produced by *g*-modes propagating to the surface of the star induced by a less massive companion.

3. DISCUSSION

The temperatures of the companions are high. If these objects are planets then we can investigate their thermal properties when the only energy source is irradiation from the star. Assuming a Bond Albedo of zero and complete redistribution of heat for reradiation, we can calculate the equilibrium temperature (T_{eq}) assuming the companions are blackbodies. The light curve does not show any indication of variability at the orbital period that might indicate a day–night temperature gradient for a tidally locked companion. The calculation of T_{eq} estimates the temperature of the planet assuming the only energy input is flux from the host star. For KOI-74b this gives an equilibrium temperature of 2250 ± 50 K, and 1715 ± 50 K for KOI-81b. Comparing these values to the measured effective temperatures allows us to conclude that the objects require an additional energy source. This could indicate prior evolution of the companions and we are watching them slowly cool.

Figure 3 shows the positions of the host stars and companions relative to stars, planets, and WDs. The green and cyan points are previously known transiting extrasolar planets[16] and their host stars. The dark blue points show the first five *Kepler* extrasolar planets (Borucki et al. 2010a). The red diamonds indicate the Earth, Uranus, Neptune, Saturn, and Jupiter. The magenta points mark low-mass stars from Lopez-Morales (2007). The black circles clustered near $1\,M_\odot$ are WDs observed by *Hipparcos* (Provencal et al. 1998) and those near $0.2\,M_\odot$ are a sample of extremely low-mass WDs (Edmonds et al. 2001; Bassa et al. 2006; Liebert et al. 2004; Kawka & Vennes 2009; van Kerkwijk et al. 1996) that have degenerate companions. The orange lines, from top to bottom, show zero-temperature WD models of Zapolsky & Salpeter (1969) with compositions of H, He, Mg, C,

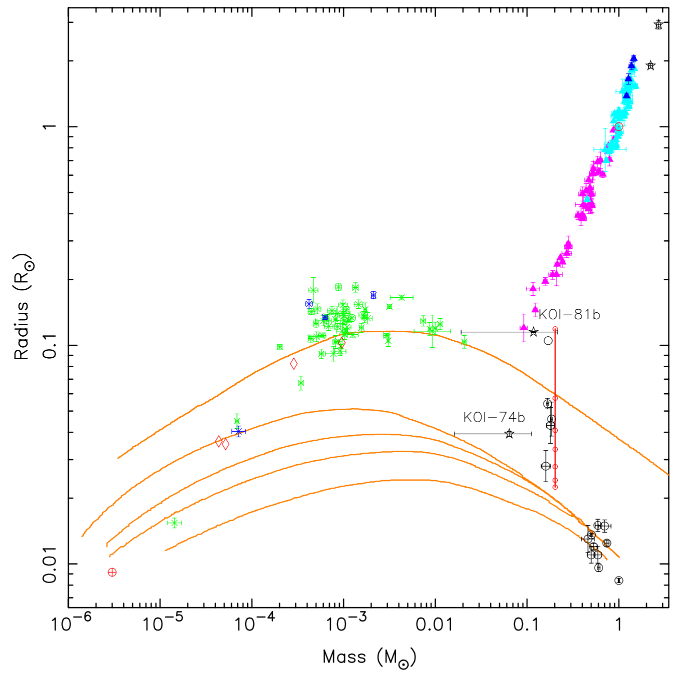

Figure 3. Location of KOI-74b and KOI-81b on the mass–radius diagram: stars with transiting exoplanets are shown in cyan and transiting exoplanets with well-defined masses and radii are shown in green. *Kepler* transiting planets are shown in blue. The positions of the Earth, Uranus, Neptune, Saturn, Jupiter, and the Sun are also indicated by red diamonds. Low-mass stars from Lopez-Morales (2007) are shown in magenta. WDs as observed by *Hipparcos* (Provencal et al. 1998) and a sample of extremely light WDs are shown with black o's. The open circle near KOI-81b is the millisecond pulsar companion discovered by Edmonds et al. (2001). The orange lines, from top to bottom, show zero-temperature models of Zapolsky & Salpeter (1969) with compositions of H, He, Mg, C, and Fe. The red vertical line is the cooling curve for a $0.2026\,M_\odot$ He-WD from Panei et al. (2007). KOI-74 and KOI-81 are shown as stars in the upper right portion of the diagram and the positions of KOI-74b and KOI-81b are labeled.

(A color version of this figure is available in the online journal.)

and Fe. The red vertical line is the cooling curve for a $0.2026\,M_\odot$ He-WD from Panei et al. (2007). The red vertical line shows the cooling model for a He-WD with a mass of $0.2026\,M_\odot$ formed through mass transfer (Panei et al. 2007). The stars KOI-74 and KOI-81 are denoted in the upper right portion of the diagram by black stars and the positions of the companion KOI-74b and KOI-81b are labeled.

The position of KOI-81b in the mass–radius diagram is similar to low-mass stars at the hydrogen burning limit but its inferred temperature is much higher. It has similar physical properties to the cooling He-WD discovered in the globular cluster 47 Tuc by Edmonds et al. (2001). Stellar modeling from the $\rho_\star$ (Borucki et al. 2010b) method puts the age of the host star at 340 ± 67 Myr. The observed mass and radius of the companion estimate $\sim$155 Myr since its creation from the cooling curves of Panei et al. (2007). KOI-74b and KOI-81b orbit at distances of $16\,R_\odot$ and $49\,R_\odot$, respectively. When the hot stars begin shell burning of hydrogen in their interiors, their radii will dramatically increase and will likely result in mass transfer to the companions. That these objects are both found around hot stars is intriguing. The companions are inundated with UV radiation from the host star and are likely suffering from substantial evaporation and ionization.

The light curve for KOI-81 shows significant power near 0.72 c day^{-1}. There may be stellar pulsations induced by tidal interactions with the companion similar to the activity has been seen in the F-type binary star system HD 209295 (Handler et al.

[16] The Extrasolar Planets Encyclopedia: http://www.exoplanet.eu.

2002). Observations of stellar oscillations offer the opportunity to refine the stellar parameters through asteroseismology.

KOI-74 and KOI-81 are interesting astrophysical systems. Confirmation of the companion masses with spectroscopic radial velocities will help confirm the physical properties of these objects. Follow-up observations are planned as well as continued with the *Kepler* instrument to help unravel their nature.

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Facilities: Kepler

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